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Magnetic Insulation Experiments with a Traveling Magnetic Piston Plasma Accelerator

8 MAY 1963

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Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

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ABSTRACT

~~This paper reports on~~ Further experimental work on ~~a~~ traveling magnetic piston plasma accelerator is reported. This accelerator produces a shock wave traveling at ~~1.1 × 10⁷~~ 110,000,000 cm/sec. ~~Ideally, that is, if there were no plasma losses and if the piston has a flat face normal to its motion, the accelerator would produce a 12-cm long uniform plasma slug filling the shock tube cross section. Actually, the magnetic piston face is not flat.~~ Since the effective length of the piston is of the same order as the ideal length of uniform plasma, the plasma will expand to fill the tube cross section when the piston stops; this will produce a non-uniform slug even if there is no loss of plasma.

In an attempt to inhibit the flow to the boundary layer, a uniform axial magnetic field was put on the shock tube. This applied magnetic field also alters the piston shape as well as the plasma leakage through the piston. ~~It is difficult to determine from preliminary experiments which effect is responsible for the observed changes in the flow; nevertheless, the experimental data are interesting. These~~ The data indicate that for certain orientations and strengths of axial magnetic field, the attenuation of shock wave velocity beyond the exit of the accelerator is markedly reduced. ~~Experimental data taken with streak camera and Kerr Cell are shown.~~

CONTENTS

FIGURES

I. INTRODUCTION

This paper describes some further experimental work on a traveling magnetic-piston plasma accelerator previously described in three papers by Mayfield et al. (Refs. 1, 2, and 3). The object of these experiments is to magnetically insulate the highly ionized gas flow in the plasma accelerator from the cold boundary layer at the wall of the shock tube. This insulation is to be achieved by applying a uniform axial magnetic field throughout the shock tube.

The accelerator described in References 1, 2, and 3 uses a traveling magnetic field (magnetic piston) to accelerate a hydrogen plasma to a velocity of 1.1×10^7 cm/sec. This field is produced by discharging a bank of capacitors that forms, with a doubly wound solenoid surrounding the accelerator duct, a transmission line network having a constant propagation velocity. Initially, the plasma is created by firing a Josephson-type conical discharge tube (Ref. 4). The resulting shock wave propagates into one end of the accelerator duct. At the appropriate time the transmission line is shorted, and the accelerator acts as a piston in pushing the plasma. Ideally, if there were no loss of plasma, the piston would trap all of the plasma that appears between it and the shock wave. The plasma would then travel at the piston velocity. If, in addition, the piston had a flat face normal to its motion, the accelerator would produce a 12-cm long uniform plasma slug filling the tube cross section. If such a uniform plasma slug were produced, the shock wave would propagate for about 30 cm beyond the accelerator with nearly constant velocity. Some slight shock wave deceleration would occur due to the well-known interaction among the boundary layer, the hot gas, and the shock wave (Refs. 5, 6, and 7). After this 30 cm of nearly constant velocity, strong velocity attenuation would probably occur; caused by an expansion wave generated when the piston stops moving.

It is experimentally observed, however, that as the shock wave exits from the accelerator, there is an immediate onset of strong shock wave

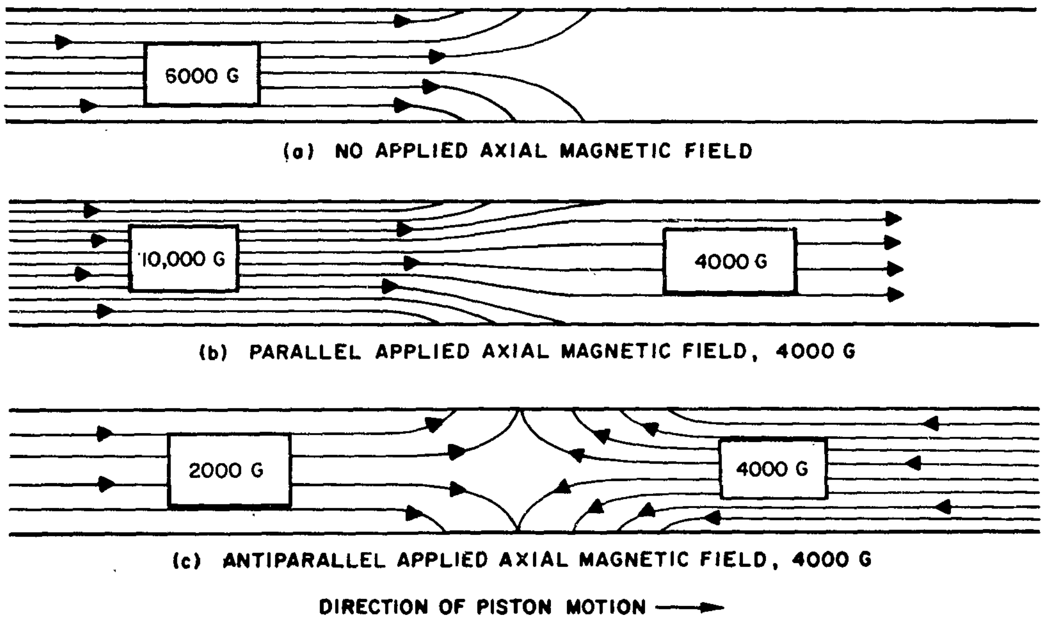


Fig. 1. Configurations of Magnetic Field Lines in Magnetic Piston

deceleration. The attenuation observed is slightly smaller than that which occurs if the conical discharge tube alone is fired (that is, if the magnetic piston is not used on the plasma).

This attenuation may have several causes. First, there is the interaction among the boundary layer, the hot gas, and the shock wave. However, the attenuation to be expected from this interaction is only a small fraction of that observed. Some attenuation can also be attributed to the fact that the piston face is funnel shaped rather than flat (Fig. 1a).

If the plasma slug is long compared with the depth of the funnel-shaped piston, as depicted in Fig. 2a, then, when the piston stops, the shock wave will propagate with only slight deceleration for some time; after this time, severe shock deceleration will probably begin, caused by an expansion wave generated when the piston stops. If the shock wave is positioned near the front of the piston (if the plasma slug length is of the same order as the piston depth) as depicted in Fig. 2b, then, when the piston stops, the shock wave deceleration caused by expansion of the plasma to fill the tube cross section will begin immediately. If the shock wave is positioned deep in the piston (i.e., if the plasma volume is very small), as depicted in Fig. 2c, the effect will be even more severe shock wave deceleration.

Since the effective depth of the magnetic piston (Fig. 1a) is probably of the same order as the ideal length of plasma slug, shock wave deceleration would probably be evident at the end of the accelerator even if there were no plasma losses.

Roshko (Ref. 8) and other workers have pointed out a mechanism whereby under some conditions in ordinary shock tube flow a drastic reduction of slug length occurs because of loss of test gas. Briefly, this reduction is caused by mass flow of the hot gas behind the shock wave to the cold walls where the viscous boundary layer then carries it past the piston. Since Roshko's analysis contains all of the essential features of the flow in this problem and since the corrections to his work given by others are negligible for these conditions, a calculation from his work will give an order of magnitude estimate of the slug

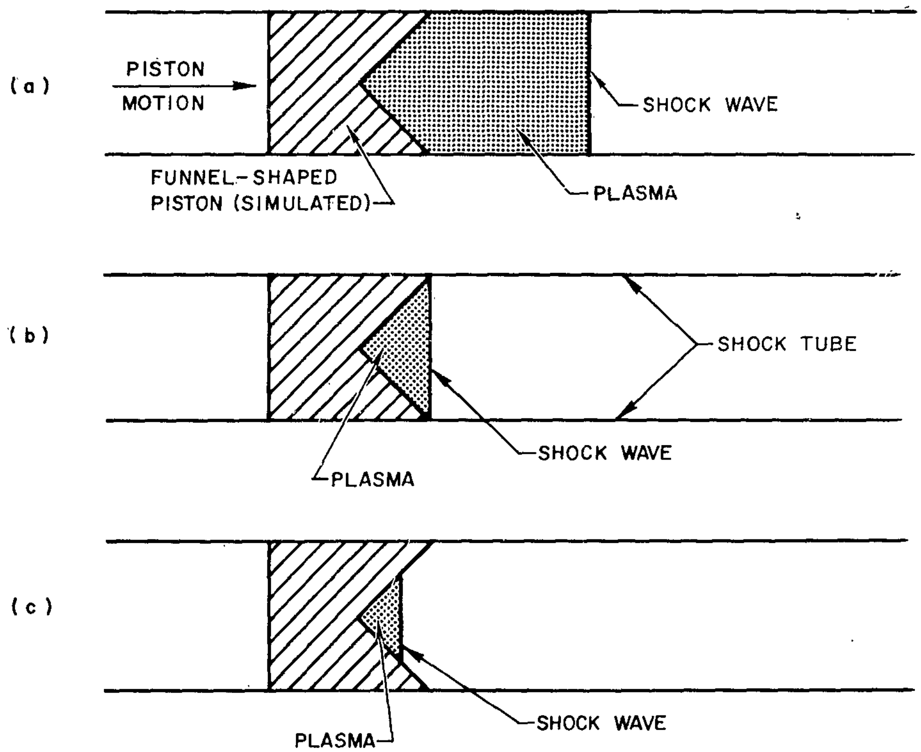


Fig. 2. Mechanical Piston Illustrating Effective Depth of Actual Magnetic Piston and its Effect on Various Plasma Slug Sizes

length with a flat-faced piston. The calculation yields 2-1/2 mm as an estimated slug length. This is several orders of magnitude less than the slug length for the ideal case, hence, this probably represents an extremely important loss mechanism. It is true that the funnel-shaped magnetic piston offers some insulation to the hot plasma. However, the field strength in the forward portion of the piston is considerably weaker than the strength probably necessary to insulate the flow.

Plasma can also become lost by another mechanism, passage through the region of radial magnetic field (i. e., by diffusion through the magnetic piston). It is difficult to determine how much plasma is lost this way although it is clearly an important consideration (see Ref. 9 for a partial analytical discussion). If the loss of plasma by radial mass flow to the boundary layer is responsible for a major fraction of the losses that occur, then this radial flux of plasma can in principle be inhibited by applying an axial magnetic field.

It is realized that the application of this axial magnetic field will also affect other aspects of the experiment; for instance, the configuration of magnetic field lines in the magnetic piston will be altered. The effects of this and of other changes caused by the application of the axial magnetic field are discussed in Section III.

It was believed that this rather preliminary experiment performed on the existing plasma accelerator would produce interesting results despite the fact that it would be difficult to determine which effect was responsible for the observed changes in the flow.

II. TYPICAL VALUES OF FLOW VARIABLES

Assuming equilibrium conditions behind the shock front, one can calculate the flow properties in the absence of a magnetic field by using charts of the flow variables behind a normal shock in hydrogen (Ref. 10). The initial conditions and values of some of the parameters determined in this way are:

Conditions Ahead of Shock

$P_1 \simeq 175\ \mu$

$T_1 \simeq 300^{\circ}K$

Observed Shock Velocity

$U_s \simeq 11 \times 10^6$ cm/sec

$M_s \simeq 72$

Equilibrium Conditions Behind Shock

$P_2 \simeq 1.2$ atm

$T_2 \simeq 70{,}000^{\circ}K$

$U_2 \simeq 8.5 \times 10^6$ cm/sec

$M_2 \simeq 2$

α(% ionization) $\simeq$ 100%

$\omega_{ce}\tau_e \simeq 7.5B \times 10^{-2}$ (B is magnetic field in G)

$\sigma_2 \simeq 10^4$ mhos/m

where M is the Mach number, ω_{ce} is the electron cyclotron frequency, and τ_e is the electron mean free time.

No effort is made here to analyze the complicated interaction that occurs between the flow of plasma and the magnetic field. However, a crude indication of the effect of the axial magnetic field on some flow properties can be given by some simple calculations. Spitzer (Ref. 11) has given the relation for the thermal conductivity transverse to a magnetic field as

$$k = k_o\left(\frac{1}{1 + \omega_{ce}^2\tau_e^2}\right)$$

where k_o is the thermal conductivity in the absence of a magnetic field. From this relation, if $\omega_{ce}\ \tau_e$ is evaluated at equilibrium conditions behind the shock, it can be calculated that a magnetic field of 50 G would reduce the thermal conductivity by one order of magnitude. Also, the ambipolar diffusion coefficient transverse to a magnetic field (Ref. 12) is found by multiplying the coefficient in the absence of a magnetic field by the factor

$$\frac{1}{\epsilon_o}\left(\frac{1}{1 + \omega_{ce}^2\tau_e^2}\right)$$

From this relation, it can be calculated that a magnetic field of 500 G should reduce the coefficient by one order of magnitude. In this relation, ϵ_o is a dimensionless factor that is fairly insensitive to the nature and temperature of the gas; its value is about 10^{-2}. It should be remembered that these are crude calculations; however, they do indicate that field strengths of several thousand gauss will probably substantially affect the flow.

III. EXPERIMENT

A. ACCELERATOR

As stated in Section I, the plasma is initially created by firing a Josephson-type conical discharge tube, which uses an 8-μF, 25-kV capacitor bank as an energy source. The resulting shock wave propagates down the shock tube, which has a 2-1/4 in. i. d. and is about 8 ft long. The initial pressure of hydrogen in the shock tube is about 175μ. When the shock wave has traveled approximately 30 cm, it is inside of the accelerator, which is then activated by a separate firing signal.

If the shock wave velocity has decreased to less than the propagation velocity of the transmission line, the magnetic piston will then catch the shock wave from behind and push the plasma. At the end of the accelerator the piston stops abruptly, and the shock wave continues to move down the shock tube.

From past experimental results it is known that the accelerator produces shock wave velocities beyond the accelerator that vary by about 20 percent from run to run for the same imposed conditions. From past experiments in this laboratory it is clear that this nonreproducibility can be attributed primarily to the conical discharge tube. The magnetic piston is essentially identical from run to run. This nonreproducibility is reflected in the results of this experiment.

It has also been found that the attenuation of the shock velocity beyond the accelerator is sensitive to the time that elapses between firing of the conical discharge tube and activation of the accelerator, as would be expected. Because of the nonreproducibility of the conical discharge, there is no one delay time that is best for all shock waves. However, a delay time can be established that is best for the greatest percentage of shock waves at a given condition. This delay time for no applied axial magnetic field is 5 μsec.

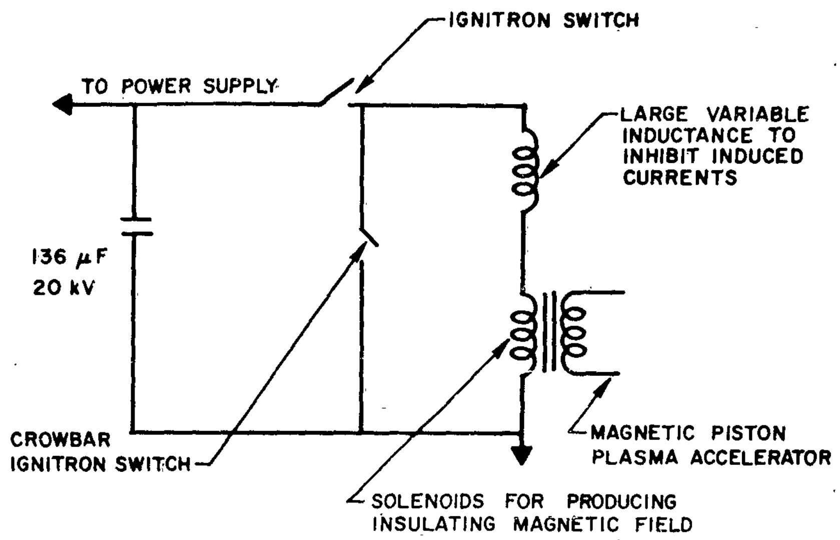


Fig. 3. Schematic of Circuitry for Producing dc Magnetic Field

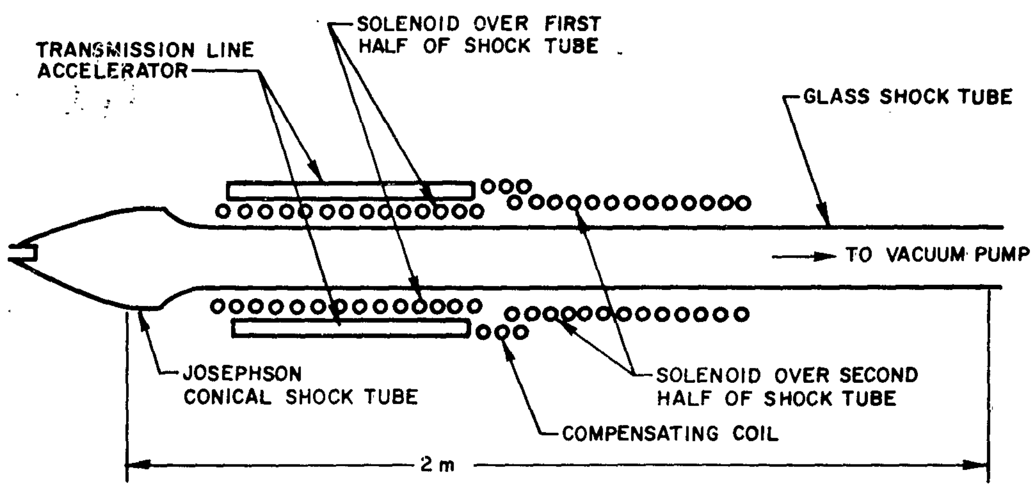


Fig. 4. Schematic of Apparatus

B. INSULATING MAGNETIC FIELD

A pair of solenoids connected in series and energized by a 20-kV, 136-μF capacitor bank produce the insulating magnetic field in the shock tube. A schematic diagram of this circuit is shown in Fig. 3. The frequency of the current in this circuit is sufficiently low that one cycle of the accelerator is accomplished while the insulating field is essentially constant at its maximum value. The capacitor bank is designed so that values of insulating magnetic field ranging from 500 to 15,000 G can be applied. The actual strength of magnetic field for any given run was determined from an oscilloscope trace showing the time integrated signal from a small calibrated coil that was positioned on axis at the midplane of an external solenoid.

One of the solenoids on the shock tube is positioned inside the accelerator duct so as to provide the insulating magnetic field over that portion of the shock tube. The other solenoid is positioned over the second half of the shock tube; i.e., over that part not inside the accelerator. A compensating coil assures that the magnetic field inside the shock tube is approximately uniform in the vicinity of the common end plane of these two solenoids. A sketch of the relative locations of the main elements of the apparatus is shown in Fig. 4. A photograph of the apparatus is shown in Fig. 5.

As a result of the solenoid arrangement, when the accelerator is fired, the resulting traveling magnetic field induces a large voltage in the solenoid positioned inside the accelerator. In order to minimize the current resulting from this large induced voltage, two things were done. First, a large stepwise variable inductance was connected in series with the two solenoids on the shock tube; this provided a large impedance to transient voltages induced by the accelerator. Second, since the induced voltage is proportional to the product of the self-inductance of the solenoid inside the accelerator and the already fixed self-inductance of the transmission line, an attempt was made to minimize the self-inductance of the solenoid inside the accelerator duct. Since the diameter of this solenoid is more or less fixed by the geometry, the winding density must be reduced in order to reduce the self-inductance.

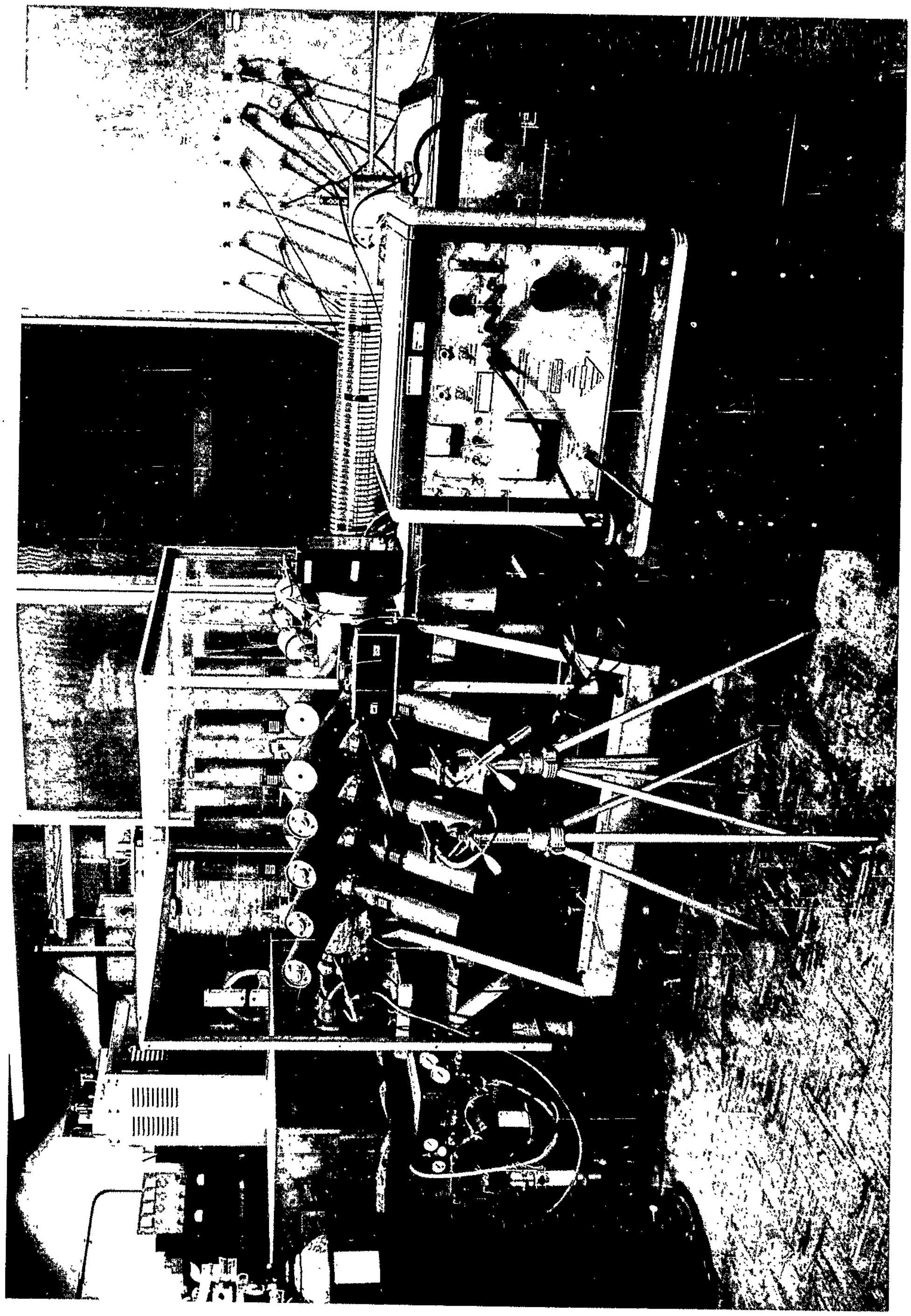


Fig. 5. Photograph of Apparatus

In order to accomplish this reduction without producing strong spatial variations in the magnetic field distribution inside the solenoid, three identical coils wound on the same cylindrical winding form were connected in parallel. The resulting effective spacing between windings is one third of that for one of the coils; the overall self-inductance of the solenoid is approximately the self-inductance of one of the three coils.

The induced current must be kept to a minimum for two reasons: (1) to prevent any sizable fluctuation in the strength of the insulating magnetic field; and (2) to prevent the absorption of an appreciable fraction of the energy from the magnetic piston, thus weakening its interaction with the flow. The value of the impedance is varied so that the perturbation in the axial magnetic field strength due to the induced current is always 10 percent or less. For all the conditions encountered in the experiment, the impedance was sufficiently large that the piston interaction with the flow was not altered by any loss of energy from the magnetic field of the accelerator. This was determined experimentally.

C. PLASMA INJECTION

As the shock wave leaves the conical driver it immediately enters the region of increasing magnetic field strength produced by the insulating magnetic field coil. If the magnetic field is strong enough, the plasma will be channeled by the fringing field; that is, it will be compressed toward the axis as it propagates further into the magnetic field. This channeling will result in acceleration of the shock wave and plasma. Also, because it is channeled, the shock wave velocity will attenuate more slowly than it would without an insulating field. An experiment was made to determine the shock wave motion under these conditions, that is, for various magnetic field strengths without using the accelerator. It was found that the average shock velocity in the accelerator duct increases monotonically with applied field strength. The results are shown in Fig. 6.

One result of the higher shock wave velocities in the shock tube is a different optimum delay time for firing the accelerator for the various applied

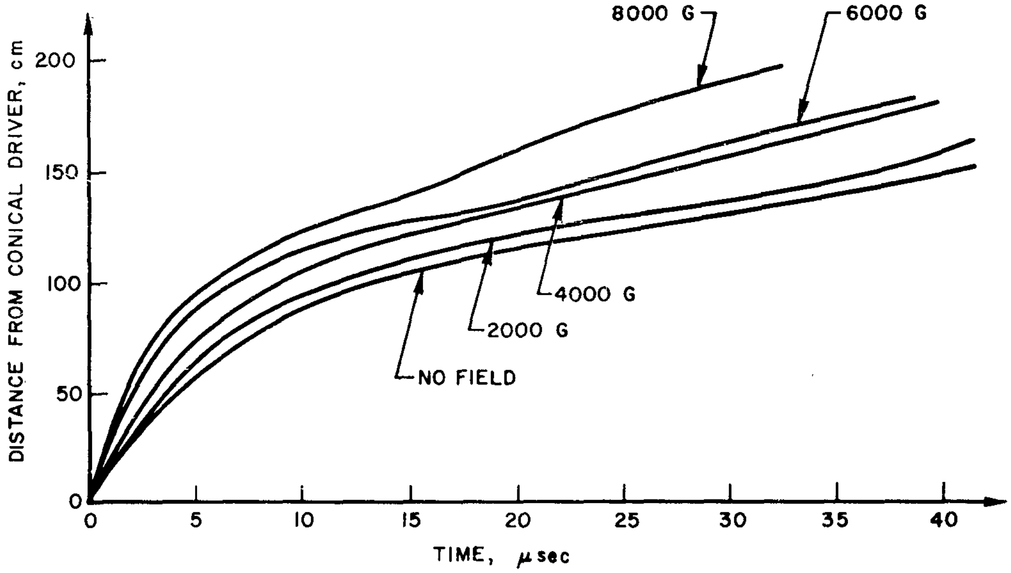


Fig. 6. Shock Velocities at Various Magnetic Field Strengths With Only Conical Driver Fired

magnetic field orientations and strengths. Consequently, experiments were made to determine the best delay time for each setting of the orientation and strength of the applied magnetic field. All data reported herein was taken using the optimum delay time for the particular conditions. Also, it can be seen that, because of the channeling of the plasma at the higher magnetic field strengths, the plasma will be concentrated near the axis when the magnetic piston begins pushing on it. This will be true regardless of the orientation of the applied field. Depending on the details of the piston-plasma interaction, the plasma may or may not remain concentrated near the axis.

D. MAGNETIC PISTON CONFIGURATION

The actual configuration of magnetic field lines in the magnetic piston with no applied axial magnetic field resembles that shown in Fig. 1a. The maximum value of the radial component of magnetic field in the piston is about 1500 G and the value of uniform axial magnetic field behind the piston is 6100 G. It can be seen that the application of a uniform, axial, insulating magnetic field will change the configuration of the magnetic field lines in the magnetic piston. The resulting configuration will depend on the strength and orientation of the applied field. If the vector direction of the applied field is in the same direction as that of the axial field produced by the accelerator, it is defined as a parallel orientation; in the opposite direction, an antiparallel orientation. Several examples of possible piston configurations are shown in Fig. 1.

Different configurations will produce different piston interactions with the flow. It is difficult to evaluate the relative effect of these different configurations, but some qualitative statements can be made. If the applied magnetic field is in the parallel orientation (Fig. 1b), the field strength at all points in the piston is greater than in the case of no applied field. Hence, although the radial component of magnetic field is unchanged, the piston is probably more leaky since the $\vec{j} \times \vec{B}$ force due to plasma motion through the piston tends to channel the plasma more strongly. This stronger channeling tends to bring the plasma into regions of weaker radial magnetic field,

i. e., into regions near the axis. Because of the increased strength of the axial component of magnetic field everywhere, there will probably be a decreased diffusion of plasma to the cold walls of the shock tube.

If the applied field is in the antiparallel orientation and if its strength is between zero and 6100 G, then a cusp geometry results, as shown in Fig. 1c. In the forward portion of the cusp where the axial magnetic field is antiparallel, the $\vec{j} \times \vec{B}$ force on the plasma has a positive radial component tending to push the plasma toward the tube walls. Any positive radial motion of the plasma will bring the plasma into regions of higher radial magnetic field strength; this would appear to decrease plasma losses through the piston itself. If the plasma is in the back portion of the cusp, the $\vec{j} \times \vec{B}$ force is radially inward and the same reasoning applies here as in the case of the parallel orientation. For applied field strengths above 6100 G antiparallel, the cusp geometry no longer occurs, and the $\vec{j} \times \vec{B}$ force has a positive radial component everywhere in the piston. The axial component of magnetic field is still present, however, and will tend to reduce plasma losses to the walls.

It is quite possible that the shape of the piston will affect the plasma motion when the magnetic piston stops. The plasma may be retarded and expanded or compressed depending on the configuration of magnetic field lines.

E. OBSERVATIONS

During the acceleration phase, the position of the magnetic piston is monitored by radial field probes; and the position of the shock wave, by photomultiplier tubes. There are seven equally spaced portholes along the axis of the accelerator through which the photomultiplier observations are made. The field probes are positioned outside the accelerator at the same axial position as the photo tubes. The simultaneous display on a dual beam oscilloscope of phototube and field probe signals from each of two axial stations shows the relative positions of the magnetic piston and the shock wave at those stations.

After the shock wave exits from the accelerator, its positon is recorded by a revolving mirror streak camera. From this data, shock wave velocity as

a function of distance from the end of the accelerator can be deduced. A Kerr Cell is used to photograph plasma luminosity as the shock wave exits from the accelerator. This Kerr Cell was also used to photograph the luminosity that resulted when the plasma impinged on a rake of wedges inserted in the shock tube. This rake had four identical 30 deg half-angle wedges made of Teflon and spaced at different radial positions in the shock tube. The luminosity pattern about the rake of wedges should give a preliminary indication of whether or not any gross radial gradients in flow conditions exist for various strengths and orientations of magnetic field.

As discussed above, several effects caused by the application of an axial magnetic field bring about changes in the flow conditions, and hence, changes in the shock wave velocity. In summary, these are:

1) changes in the way plasma is injected into the accelerator
2) changes in the magnetic piston configuration
3) changes in the radial mass flux of plasma to the cold boundary layer at the wall
4) changes in leakage of plasma through the piston

It is difficult to determine from this preliminary experiment which effect is responsible for the observed changes in the flow; nevertheless, the experimental data are interesting.

IV. RESULTS

Experimental data showing shock wave velocity under various conditions of applied magnetic field are presented graphically in this section. Kerr Cell photographs of plasma luminosity patterns for various cases are also shown.

In Figs. 7 and 8, shock wave velocity is plotted as a function of distance from the end of the accelerator for various orientations and strengths of applied axial magnetic field. These data show the motion of the fastest shock waves observed for each of the conditions imposed.

For applied field strengths of 2000 G or more for both orientations of the applied field, there is a monotonic increase of shock wave velocity with applied field strength at every axial station beyond the accelerator. For applied field strengths of less than 2000 G, the changes shown fall within the scatter of the data for zero applied field, and sufficient data have not been taken to establish a trend. It can be seen that the shock wave velocities show approximately no dependence on applied field orientation.

In several of these curves, there is a very noticeable decrease for a short distance in the rate of shock wave deceleration, as, for instance, in the curve for shock wave velocity at 4000 G antiparallel. In some cases, there is an actual acceleration of the shock wave followed by deceleration again. This phenomenon occurs to a small degree even when there is no applied magnetic field. This aspect of the flow is not understood; there is no hint from streak and image converter camera photographs as to the cause, and its investigation has not been pursued.

In order to illustrate the large scale nonreproducibility that occurs at higher field strengths, data showing shock wave velocity as a function of distance for several runs at the same conditions are plotted in Fig. 9. A possible cause for this nonreproducibility is discussed below.

In Fig. 10 and in subsequent wave (or x-t) diagrams of the shock wave and magnetic piston motion, the piston motion is represented as a single

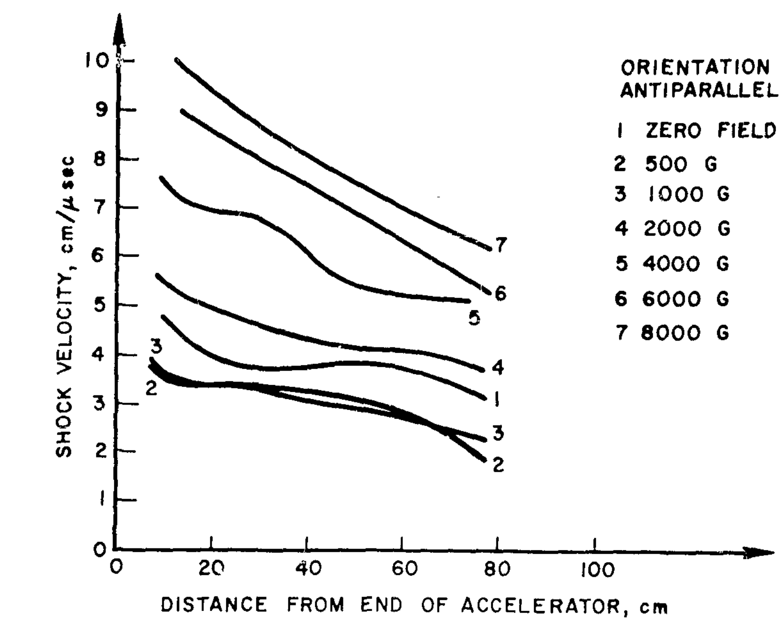


Fig. 7. Shock Velocity as a Function of Distance Beyond Accelerator for Various Strengths of Antiparallel Applied Field

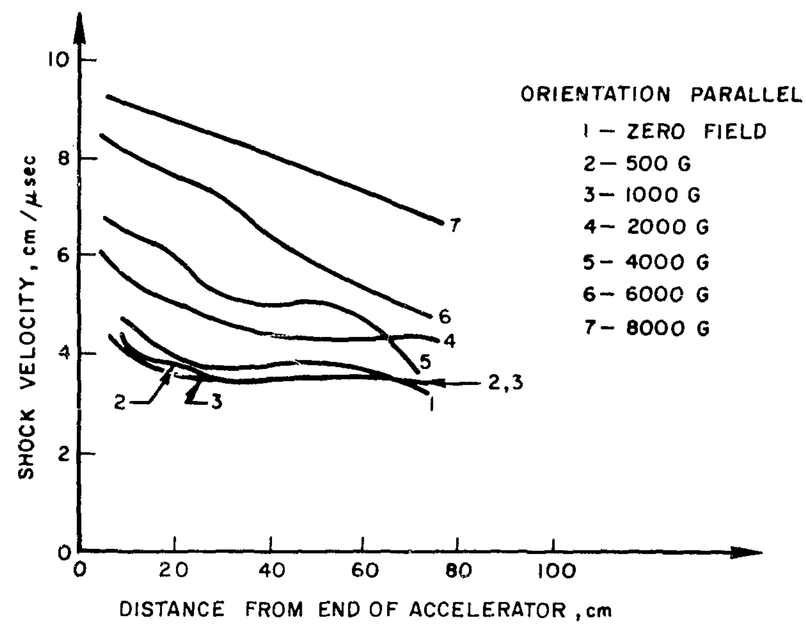


Fig. 8. Shock Velocity as a Function of Distance Beyond Accelerator for Various Strengths of Parallel Applied Field

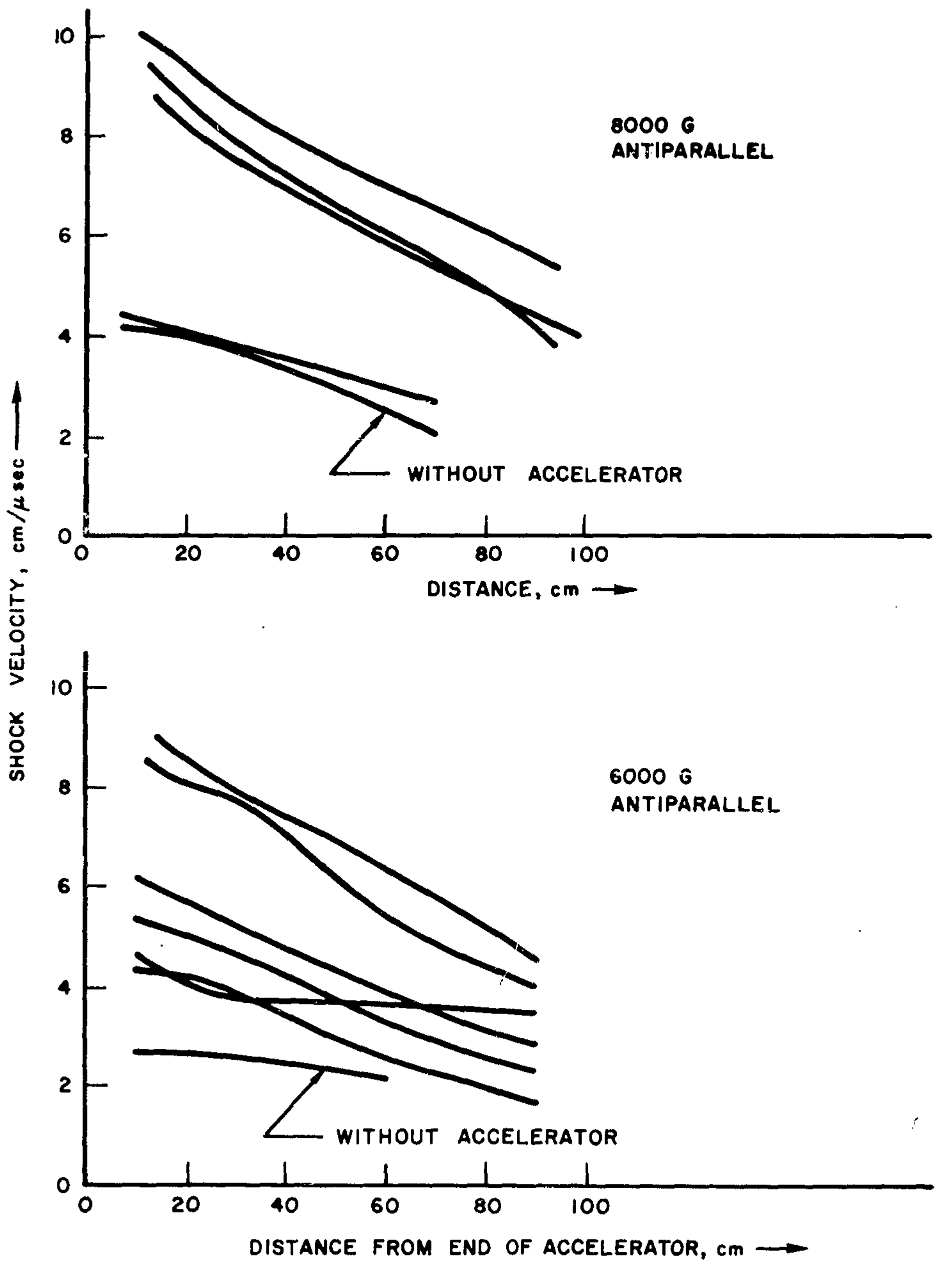


Fig. 9. Shock Velocity as a Function of Distance Beyond Accelerator for Several Runs at Same Applied Field Conditions

straight line in order to have a well-defined reference point in the piston. However, this representation is inaccurate because, as previously mentioned, the piston has a certain axial depth. Its actual depth, as determined from measurements with magnetic field probes, is about 15 cm and is shown to scale in these diagrams. The slope of the piston path is 11 cm/μsec, which is the phase velocity of the transmission line.

In Fig. 10, data are presented for the case of no applied magnetic field, comparing the wave motions with and without the use of the accelerator. When the accelerator is used, the shock wave decelerates until the piston catches up with it; the shock wave velocity then increases rapidly until it matches the transmission line phase velocity. Near the exit end of the accelerator, the shock wave seems to fall behind the piston path; however, it is still within the effective depth of the piston. A possible explanation for this early deceleration may be that the piston, experiencing dispersion as it moves along the line, increases its effective depth, thus decreasing the strength of the radial magnetic field and weakening the piston-plasma interaction.

After leaving the accelerator, the shock wave decelerates again, as shown in Figs. 7 and 8. A Kerr Cell photograph of the plasma luminosity taken just beyond the accelerator shows that the luminosity seems to be uniform across the shock tube (Fig. 11a) and that the luminosity front has a slight curvature. Successive Kerr Cell photographs at these conditions show good reproducibility. A Kerr Cell photograph taken with a rake of 30 deg half-angle wedges inserted in the shock tube (Fig. 12a), shows that the gradients in the flow conditions in the radial direction are probably not extremely large. The second photograph taken at a later time (Fig. 12b) indicates that the radial gradients in the flow conditions are probably still not extremely large.

Figure 13 is an x-t diagram in which the shock wave motion for the case of 4000 G parallel applied magnetic field is compared to that for no applied field. In this case, the shock wave, as it nears the exit end of the accelerator, falls even further behind the piston path than in the case of no

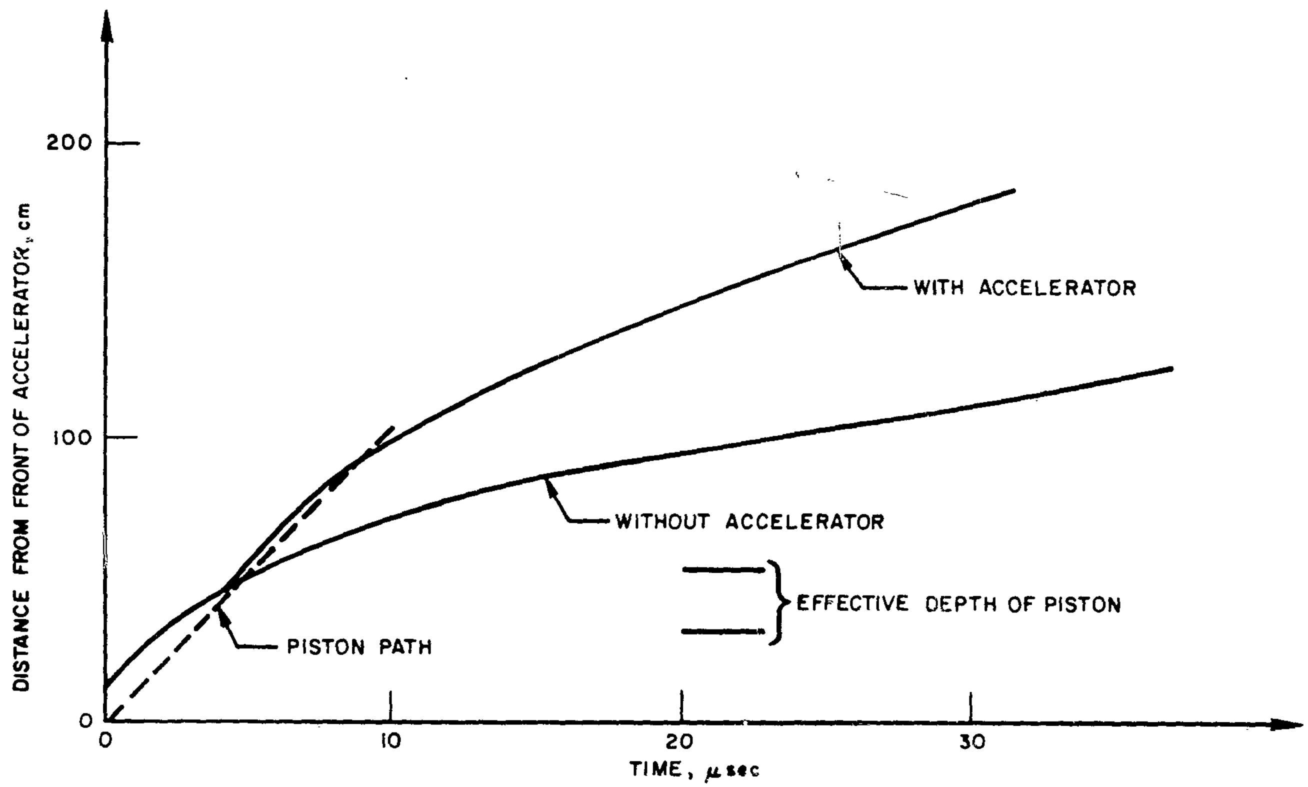


Fig. .10. x-t Diagram Comparing Wave Motions for No Applied Field With and Without Accelerator

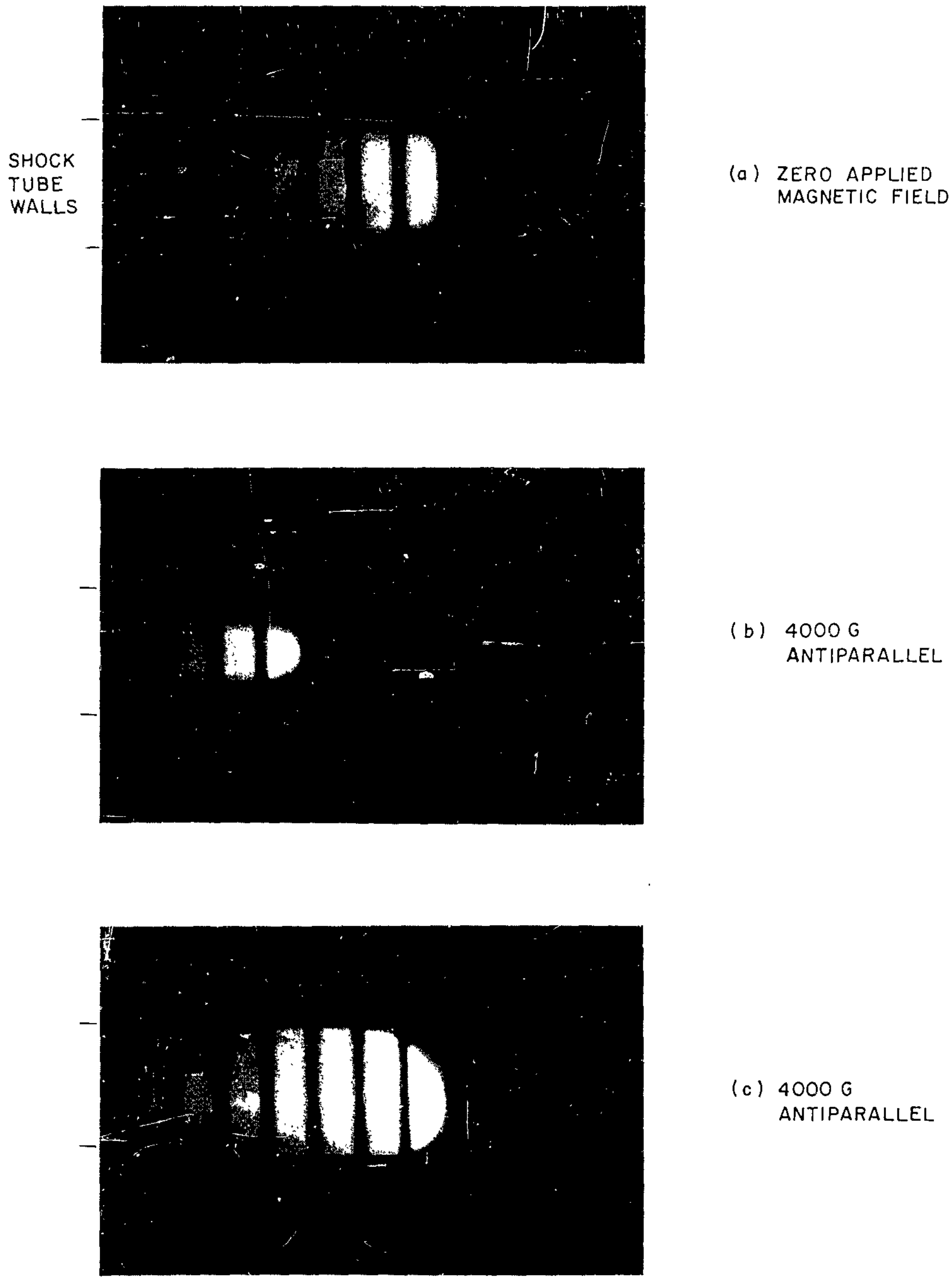
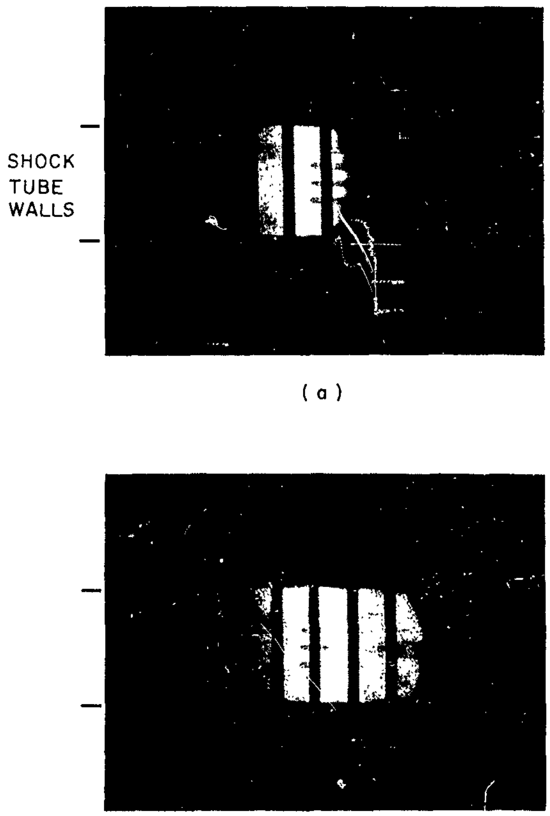


Fig. 11. Kerr Cell Photographs of Plasma Luminosity Beyond Accelerator for Various Conditions of Applied Field



(a)

(b)

Fig. 12. Kerr Cell Photographs for Two Shock Wave Positions With Four Teflon Wedges in Flow, With Accelerator and No Applied Field

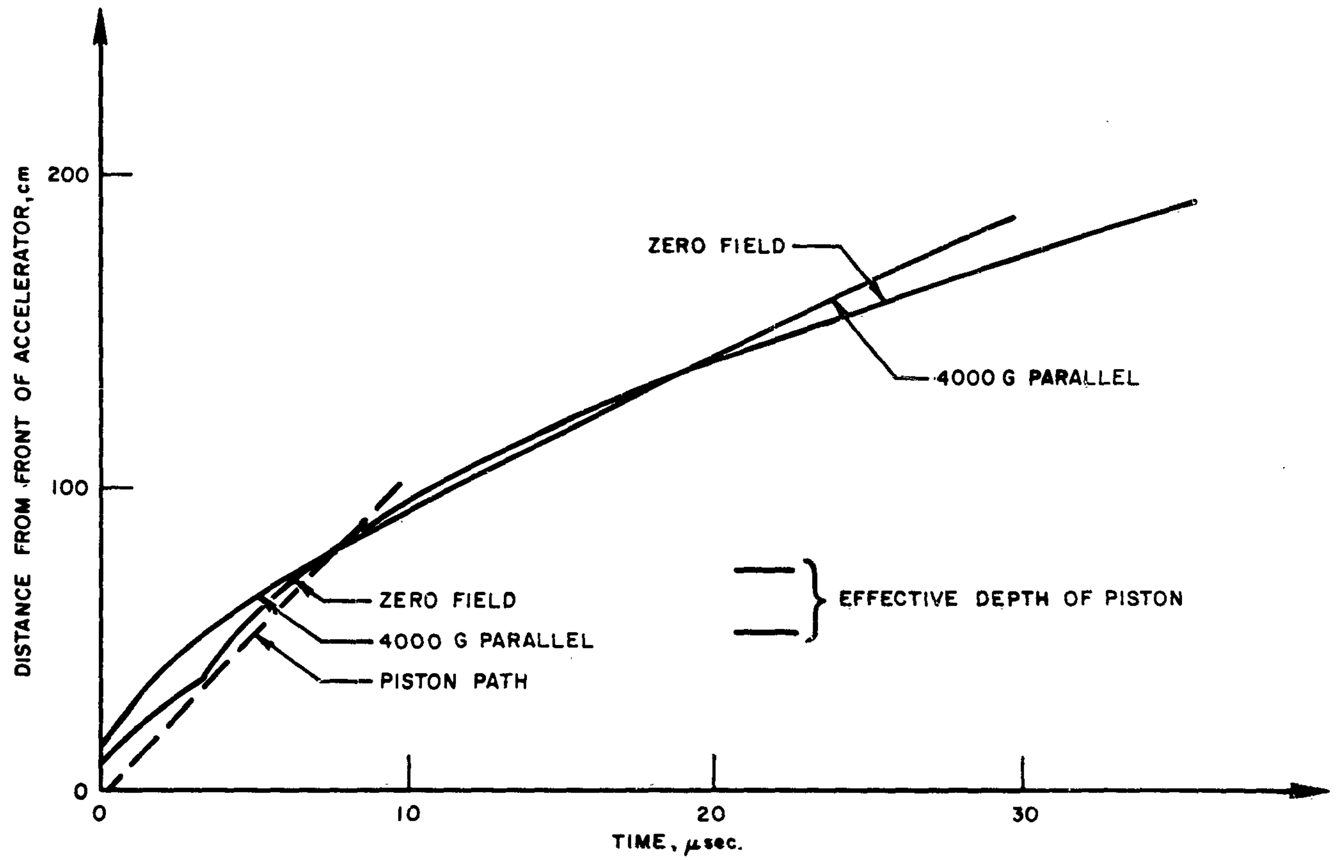


Fig. 13. x-t Diagram Comparing Wave Motions With and Without 4000 G Parallel Applied Field

applied field; however, it sustains a higher velocity beyond the accelerator, as seen in Fig. 8. A Kerr Cell photograph of the plasma luminosity just beyond the accelerator (Fig. 11b) shows that the luminosity is confined to a region near the axis of the tube; in fact, it occupies less than 1/2 of the tube diameter. A Kerr Cell photograph with a rake of four wedges in the shock tube (Fig. 14a) shows that luminosity is not evident on the wedge located outside the region of incident plasma luminosity. Figure 14b shows that this is still the case at a later time, which indicates that large radial gradients in the flow conditions probably do exist. These results are explainable in light of the following considerations:

1) the plasma is probably channeled by the fringing field as it travels into the accelerator
2) the piston for this condition tends to compress the plasma toward the axis
3) the insulating magnetic field will tend to keep the plasma from expanding to fill the shock tube when the piston stops moving

The shock wave motion for the case of 4000 G antiparallel applied magnetic field is shown in Fig. 15. In this case, the shock wave does not cross the piston path but stays well ahead of it and exits at essentially the piston velocity. A Kerr Cell photograph of the plasma luminosity (Fig. 11c) shows that the luminosity fills the tube cross section, and that the luminosity front has a strong curvature. Kerr Cell photographs with the rake of four wedges in the shock tube (Fig. 16) show that radial gradients in flow conditions are probably not extremely large. In Fig. 16a, it is seen that when the shock wave first impinges on the wedges only those in contact with glowing plasma show interaction luminosity; the uppermost wedge is not detectable by any luminosity. The appearance of nearly uniform plasma luminosity almost to the walls is reasonable if it is remembered that the piston configuration tends to push the plasma to the walls. These photographs do show that near the wall the plasma luminosity decreases markedly, probably indicating strong radial flow gradients.

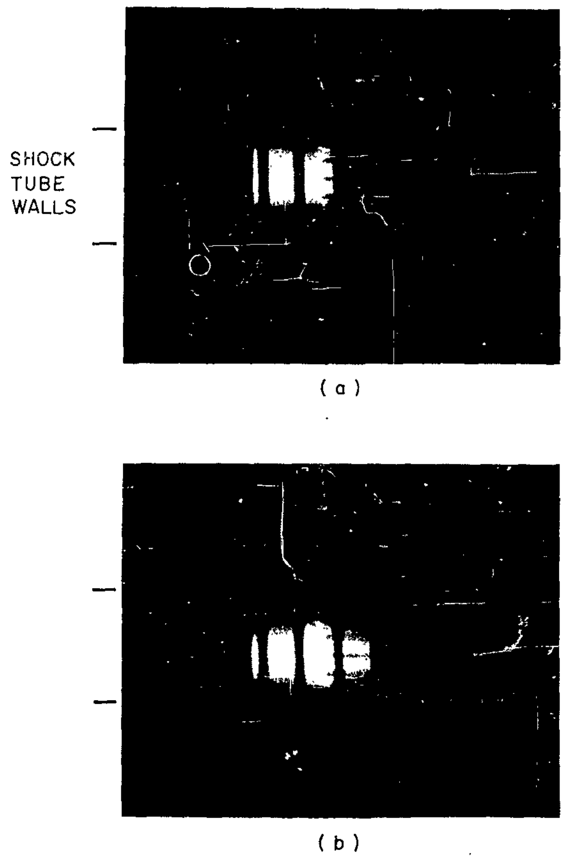


Fig. 14. Kerr Cell Photographs for Two Shock Wave Positions With Four Teflon Wedges in Flow, 4000 G Parallel Applied Field

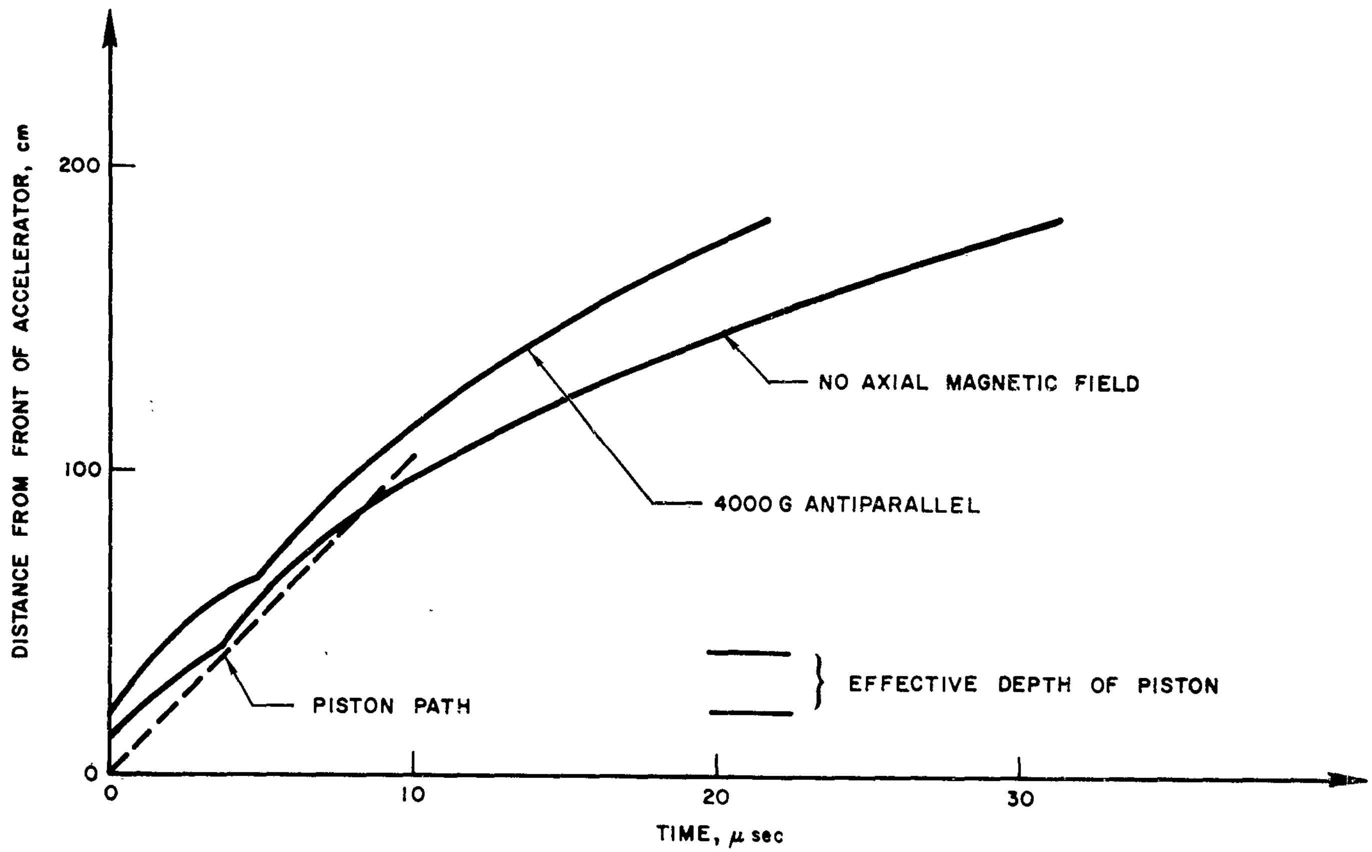


Fig. 15. x-t Diagram Comparing Wave Motions With and Without 4000 G Antiparallel Applied Field

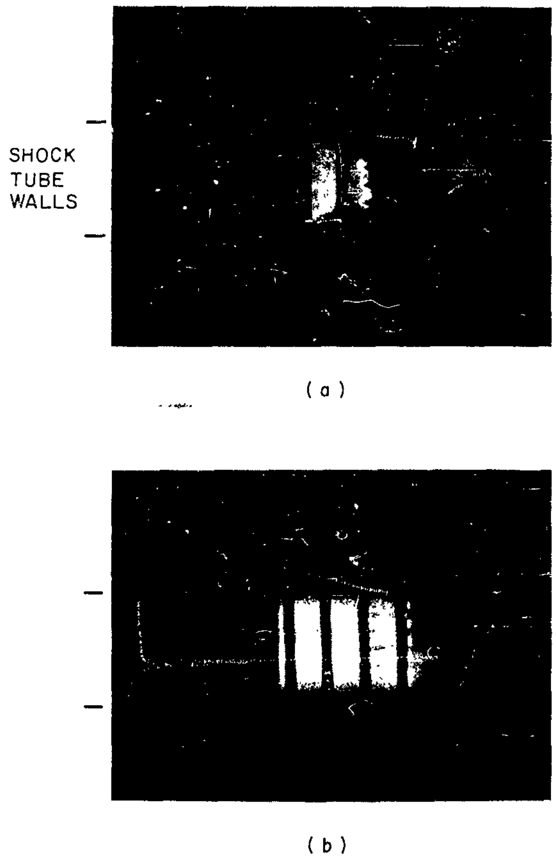


Fig. 16. Kerr Cell Photographs for Two Shock Wave Positions With Four Teflon Wedges in Flow, 4000 G Antiparallel Applied Field

An x-t diagram for the wave motion in the case of 8000 G antiparallel applied field is shown in Fig. 17. This condition of applied field is one for which large-scale nonreproducibility in shock wave velocity beyond the accelerator exists (Fig. 9a); a possible explanation for this behavior is evident in this diagram. If the average shock wave velocity in the accelerator is greater than the piston velocity when the piston is not used, then, when the piston is used, it will not catch the shock wave. Due to the nonreproducibility of shock velocities coming from the conical discharge, shocks can be produced in an applied field of 8000 G that have average velocities in the accelerator either greater or less than the piston velocity. Shocks having an average velocity in the accelerator greater than the piston velocity will not be affected by the piston, and those having an average velocity less than the piston velocity will be pushed for at least a short distance when the piston is used. The data show that the shock wave having an initially lower velocity propagates at a higher velocity beyond the accelerator than the shock that essentially does not interact with the piston. Time limitation prevented further investigation of this effect. Essentially the same condition exists with the parallel orientation at this field strength.

There is evidence that the plasma luminosity for the shock waves at 8000 G parallel occupies an even smaller portion of the shock tube diameter than at 4000 G parallel (Fig. 11b), as might be expected.

At 6000 G applied field, the channeling of the plasma as it enters the accelerator is not as severe as at 8000 G, hence the piston will almost always push on the plasma for at least a short distance; nevertheless, the variation between shock waves is sufficient to result in the nonreproducibility apparent in Fig. 9b. Kerr Cell photographs taken for both orientations of applied field at 6000 G are consistent with those taken at 4000 and at 8000 G.

The reproducibility at 4000 G and below is greater than at 6000 G and above, probably because the average shock velocity in the accelerator is always less than the piston velocity.

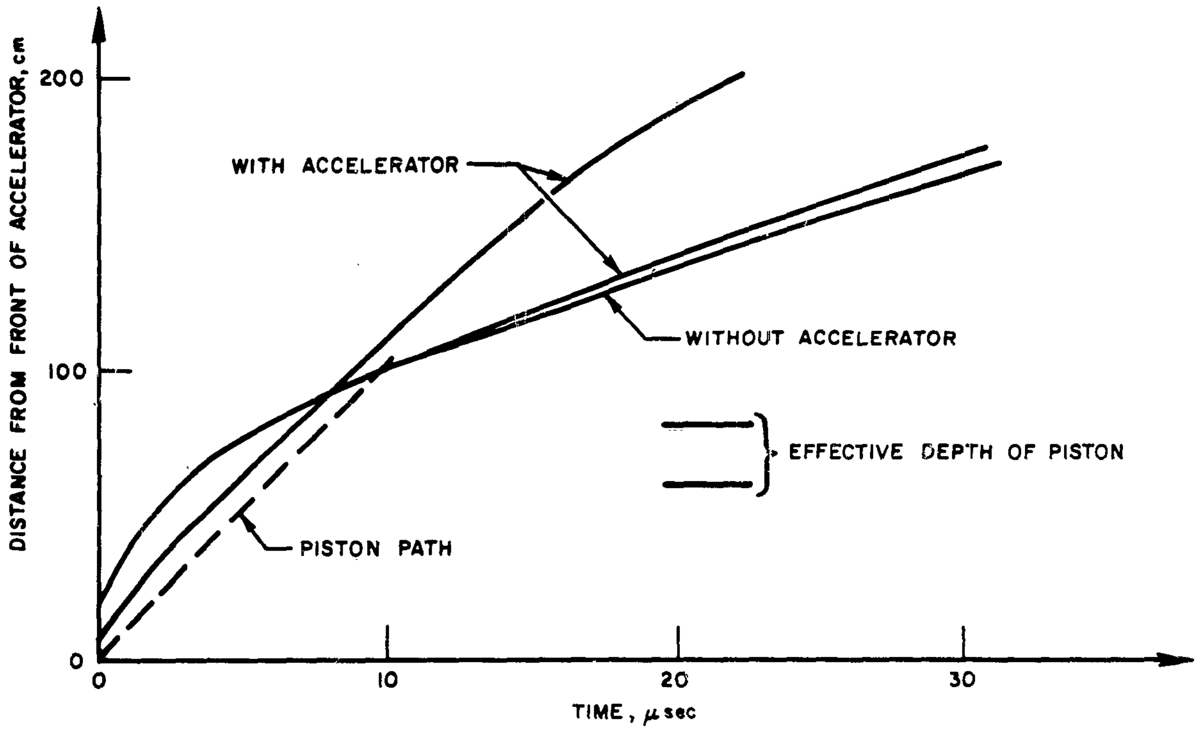


Fig. 17. x-t Diagram Comparing Wave Motions for Two Shocks of Different Initial Velocity at 8000 G Antiparallel With and Without Accelerator

Experiments were also run for field strengths up to 8000 G with both orientations of the field applied over only the accelerator half of the shock tube. The shock wave velocities beyond the accelerator show only slight dependence on applied field strength and orientation. This contrasts with the case where the field is over the entire shock tube and the exit velocity from the accelerator is increased by, say, 100 percent at 8000 G. Kerr Cell photographs (Fig. 18) show that the plasma essentially fills the tube cross section beyond the accelerator for 4000 G parallel applied field. Qualitatively, the dependence of the shock velocity on the nature of the applied field should be markedly reduced by: (1) the expansion of the plasma to fill the tube cross section beyond the end of the solenoid, thus causing shock wave deceleration; and (2) the retarding force that probably acts on the plasma as it passes through the fringing magnetic field at the end of the solenoid.

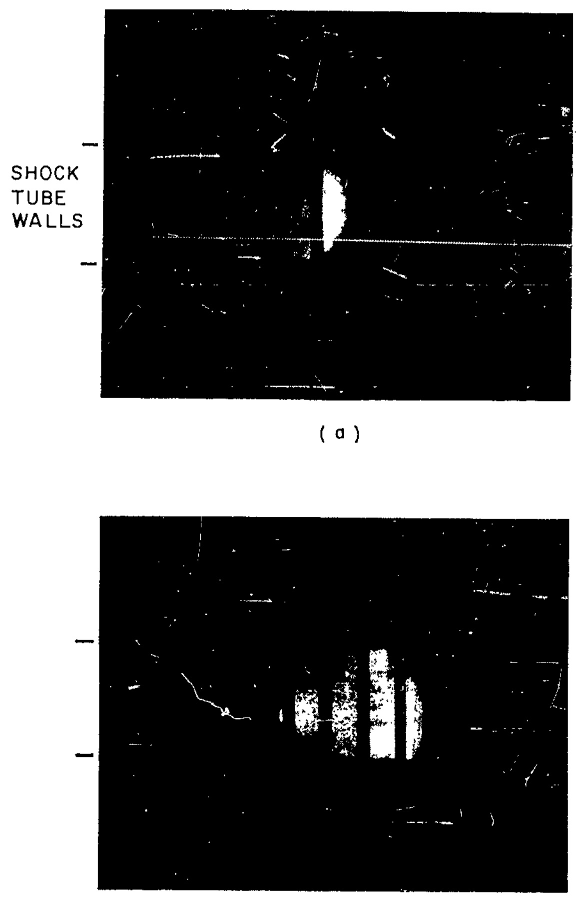


Fig. 18. Kerr Cell Photographs for Two Shock Wave Positions With Four Teflon Wedges in Flow and 4000 G Parallel Applied Field Over Half of Shock Tube

V. CONCLUSIONS

In this preliminary experiment it has been shown that:

1) the application of an axial magnetic field to the flow in a traveling magnetic-piston plasma accelerator substantially decreases the shock wave velocity attenuation beyond the accelerator

2) this decrease in shock velocity attenuation is not very sensitive to the orientation of the applied magnetic field

3) the shock wave velocity at any point beyond the accelerator increases with the strength of the applied magnetic field

It has also been shown that, for an antiparallel orientation of the applied field, the plasma probably has radial gradients near the walls, but otherwise fills the tube; and that, for a parallel orientation, the plasma tends to be concentrated within a radius that decreases with increasing field strength.

It has been indicated that if there is no applied field beyond the accelerator, the shock wave velocity has only a slight dependence on the orientation and strength of applied field. A large-scale nonreproducibility in shock wave velocity when higher field strengths are applied over the entire shock tube has been shown to exist; a possible explanation has been offered for this.

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